

A SUPERCONDUCTING SLAC WITH A RECIRCULATING BEAM*

W.B. Herrmannsfeldt
Stanford Linear Accelerator Center
Stanford University, Stanford, California

I. INTRODUCTION

The old idea of recirculating the beam in a linear accelerator becomes more interesting with the introduction of the superconducting accelerator. The long duty cycle makes it possible for the beam to go around several times. In fact, if the superconducting accelerator is operated cw, the recirculating beam could also be continuous.

The purpose of this note is to examine the practical limitations involved in recirculating a beam at SLAC in order to get the highest possible energy.

A nominal goal of 100 GeV has been chosen as a value worthy of an extensive rebuilding of the SLAC accelerator, yet low enough that good use can be made of the beam within the confines of the SLAC boundaries. Earlier in this Summer Study, Neal¹ reported on the tentative parameters of a 100 GeV superconducting accelerator, 3000 m long. It was noted that this requires an energy gradient of 33 MeV/m, a value which has yet to be demonstrated in a superconducting accelerator structure.

Interest in a recirculating beam stems from the need for an alternative way of obtaining high energy if for any reason it proves impossible or unfeasible to achieve the 33 MeV/m energy gradient. In passing, it should be noted that, although 33 MeV/m is theoretically possible for a traveling wave design in a niobium structure, there are at least two practical limitations which have not been resolved as of the date of this Summer Study. One limitation is the rf magnetic field limit, H_{c1} , at which the type II superconductor starts to go normal. The latest results, reported by Schwettman² at this Summer Study, in excess of 500 G for H_{c1} , are reasonably close to the approximately 750 G required for a TW structure at 33 MeV/m.

The second limitation is the onset of field emission for electrons from the walls of the structure. Rf energy is lost to such electrons which then strike the walls, converting the energy to heat which must be removed by the refrigeration system. An accelerator structure operating at a high energy gradient must have very low field emission or else the refrigeration demand becomes excessive. Until a structure can be operated in the accelerator mode at high enough field levels, it is essentially impossible to predict at what field level field emission could become important. Although the Fowler-Nordheim theory appears to apply,³ field enhancement due to sharp projections or foreign matter on the surface may cause field emission at fields lower than predicted from rf field calculations.

* Work supported by the U.S. Atomic Energy Commission.

1. R.B. Neal, these Proceedings, p. 101.
2. H.A. Schwettman, these Proceedings, p. 1.
3. H.A. Schwettman, J.P. Turneaure, W.M. Fairbank, T.I. Smith, M.S. McAshan, P.B. Wilson, and E.E. Chambers, IEEE Trans. Nucl. Sci. NS-14, No. 3, 336 (1967).

II. SYNCHROTRON RADIATION

The limitation on the energy of a circular electron accelerator is the loss of energy of the beam due to synchrotron radiation. Synchrotron radiation is the name given to the band of light and X-rays emitted by a beam of electrons which are being accelerated in an electromagnetic field. In the case in which the beam is caused to go in a circle, the energy loss per revolution is given by⁴

$$U = 8.85 \times 10^{-32} E^4 / r \quad (\text{eV/revolution}) \quad , \quad (1)$$

where r is the radius of curvature in meters and E is the beam energy in electron volts.

Figure 1 is a view of the SLAC site with the proposed recirculating beam superimposed using a 225 m radius for the loops. The choice of the radius is quite arbitrary, but the effect of changing it by less than a factor of two is essentially negligible for the purpose of this note. The long straight line for the return path is, of course, very simple and could be made by a tunnel-digging machine.⁵ It would contain only an ordinary vacuum pipe and some steering and focusing magnets. The magnet rings are assumed to consist of a suitable lattice of separated function bending and focusing magnets. Figure 2 shows the topographic cross section on the beam path.

The fact that the synchrotron radiation limit is reached so quickly appears to favor a separate return path rather than one which uses the accelerator tunnel. Even though the beam can be accelerated on the return path in a standing wave accelerator, the bigger, more complicated magnet rings add to the cost without apparently adding any capability.

In an earlier note⁶ on which this work is based, it was assumed that as many as three separated orbit return loops could be used. Subsequent consideration of the promise of superconducting rf structures, as described in Ref. 1, make it seem more realistic to assume that at least 50 or 60 GeV can be achieved in a single pass through the 3000 m long accelerator housing. Then only one return loop would be required to obtain 100 GeV.

Due to the high rate of synchrotron radiation, the beam energy is changing significantly within the magnet rings. Thus it is necessary to integrate the energy loss to calculate the remaining energy. From Eq. (1), the energy lost per radian is

$$\frac{dE}{d\theta} = - \frac{8.85 \times 10^{-32} E^4}{2\pi r} \quad (\text{eV/rad}) \quad , \quad (2)$$

where r is a constant. Integrating Eq. (2) over 2π radians results in

$$\left(\frac{1}{E} \right)^3 = \left(\frac{1}{E_0} \right)^3 + \frac{3 \times 8.85 \times 10^{-32}}{r} \quad , \quad (3)$$

where E is the energy after the beam has gone through both rings and is back at the injection end. E_0 is the energy the beam had as it entered the magnet ring.

4. M.S. Livingston and J.P. Blewett, Particle Accelerators (McGraw-Hill, New York, 1962).

5. T.E. Howard, Scientific American 217, No. 11, 74 (1967).

6. W.B. Herrmannsfeldt, Stanford Linear Accelerator Center Technical Note TN-68-8 (1968).

The characteristic energy of the photon spectrum of the synchrotron radiation is given by⁷

$$E_c = \frac{3hc}{4\pi r} \gamma^3, \quad (4)$$

where h is Planck's constant, c is the velocity of light, r is the effective bending radius and γ is the beam energy in units of mc^2 . An estimate for the statistical fluctuation of the emitted radiation can be found by assuming that the lost energy, $E_0 - E = nE_c$, where n is the number of photons emitted in a bend of 2π radians. The standard deviation of the emitted radiation is thus

$$\Delta E = \sqrt{nE_c^2} = \sqrt{(E_0 - E) E_c}. \quad (5)$$

The resulting spread in the beam energy is $\Delta E/E_0$. The use of E_0 rather than E is an acceptable approximation if E_0 is used in Eq. (4) to calculate γ .

Using Eqs. (3) and (5) and the parameters assumed above, it is now possible to obtain a list of parameters for a recirculating beam facility (see Table I).

TABLE I

Parameters for a Single Loop, Recirculated Beam Accelerator

Length = 3000 m
Energy gain per pass = 60 GeV
Energy gradient = 20 MeV/m
Effective radius of loop = 200 m ^(a)
Energy lost to synchrotron radiation = 4.8 GeV (360° bend)
Final energy after two passes = $2 \times 60 - 4.8 \approx 115$ GeV ^(b)
Characteristic energy of synchrotron photons = 2.5 MeV
Number of characteristic photos per electron = 1920
Quantum statistical energy spread = 109 MeV
One-loop percentage energy spread = $0.109/55.2 = \pm 0.2\%$ ^(c)
Final percentage energy spread = $\pm 0.1\%$ ^(c)

(a) Effective Radius: The effective radius is defined as the actual bending radius in the bending magnet. It was chosen as about 10% less than the radius of the beam line to permit insertion of suitable focusing magnets and drift lengths.

(b) Final Energy: Assuming 60 GeV per pass, the final energy is somewhat higher than 100 GeV. Note that the maximum possible energy of electrons which can be bent through the 200 m loops, found by setting E_0 to infinity in Eq. (3), is only 91 GeV (if we ignore quantum fluctuations).

(c) Energy Spread: At the injector end, after the first loop, the spread is $\pm 0.2\%$. After the second pass through the accelerator, the spread due just to synchrotron radiation is $\pm 0.1\%$, which is probably comparable to the spread due to all other causes combined.

7. J. Schwinger, Phys. Rev. 75, 1912 (1949).

III. MAGNET LOOPS

At this time, only enough is known about the magnet loops to permit some general remarks.

It is expected that the magnets would be dc excited for economy and stability. If conventional magnets are used, the power costs would be considerable. Attention is thereby drawn to superconducting magnets or to aluminum wire cryogenic magnets such as described by Danby.⁸ The latter would be ideally suited since the fields required are only about 10 kG.

The magnetic transport system must be both achromatic and isochronous. The isochronous (constant time) condition is required to preserve the bunched characteristic of the beam. Debunching due to velocity spread is negligible at these energies. It appears desirable to have the shortest possible focusing (betatron) wavelength in order to minimize debunching in each 180° bend. A small ($\sim 6^\circ$) reverse bend, on the long straight return path, can be used to restore the bunch structure if necessary.

The effect on transverse phase space of the emission of synchrotron radiation is to cause an increase, particularly in the horizontal plane, which will be difficult to transport through the accelerator. The accelerator steering and focusing will be constrained by the requirement that two beams will be transported simultaneously. How much can be gained by damping with the magnetic focusing system has not been determined.

This proposal has been described as "4 miles of BBU." If a transverse instability develops it may, in fact, be possible to use a feedback scheme. Such a scheme is indicated because of the cw operation and the fact that the beam takes a longer path than the signal cable from pickup cavity to amplifier.

For the beam to be accelerated on the second pass, it must have traveled an integral number of rf wavelengths. The requirement for phasing to $\lambda/100$ (about 4° of phase) requires that the path length tolerance is $\lambda/100$. In an isochronous system, the zero order path length is determined by the position of the focusing elements. The correct phase can be obtained by remotely moving some of the quadrupole lenses.

IV. CONCLUSION

The problems discussed above make it clear that it would be much preferred if the 100 GeV beam can be generated without resorting to a recirculating scheme. However, it does appear that, if necessary, a recirculating beam facility could help boost the energy to about 100 GeV. That 100 GeV is nearly the upper limit is also fairly apparent.

ACKNOWLEDGMENT

It is a pleasure to acknowledge helpful discussions with M.A. Allen, R.H. Helm, R.H. Miller, and M. Sands. R.S. Gould kindly supplied the topographic cross section.

8. G.T. Danby, these Proceedings, p. 1115.

- 1094 -

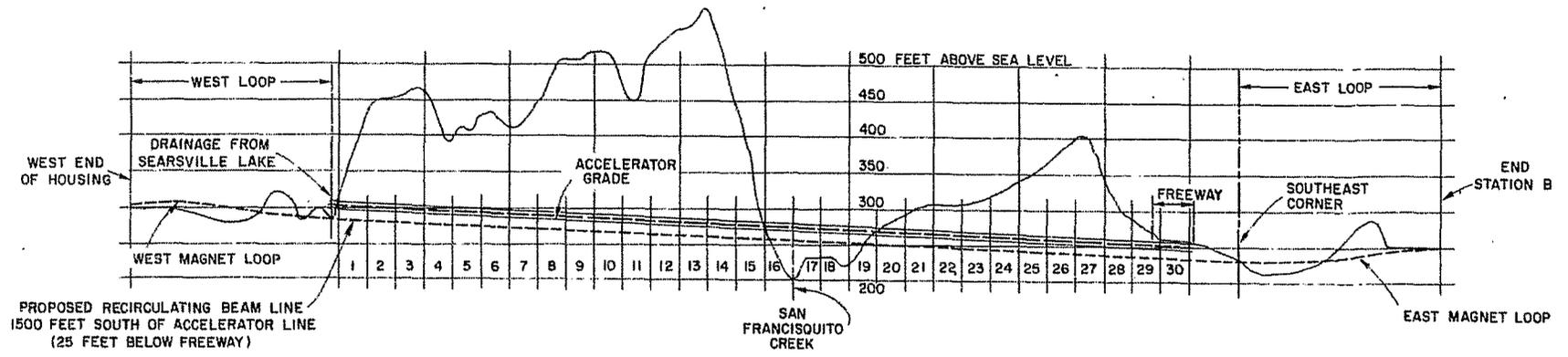


Fig. 2. Contour cross section showing the recirculating beam line from Fig. 1. Note that the loops are shown as a projection which makes the beam elevation appear to undulate.

PROPERTIES AND PREPARATION OF HIGH-PURITY ALUMINUM*

V. Arp
Cryogenics Division, Institute for Basic Standards
National Bureau of Standards
Boulder, Colorado

I. INTRODUCTION

The potential economy of using aluminum magnets operating at low temperatures was suggested by Post and Taylor¹ in 1959, before the advent of high field superconductivity. A liquid-hydrogen-cooled aluminum magnet was built and operated not long thereafter,² but by that time superconducting magnets seemed to be generally more attractive. Nevertheless, a small effort was carried on, since, for some low duty cycle conditions, aluminum appears to be more attractive than superconductors.^{3,4} We have continued a study of the properties of aluminum which are related to this type of application, and a major part of this paper summarizes this study and knowledge in a tutorial fashion. The final and minor section of the paper reports the current status on the availability of high-purity aluminum in technologically useful quantities.

II. PROPERTIES OF HIGH-PURITY ALUMINUM

In this, the major portion of the paper, electrical and thermal conductivities of metal are discussed, and data relevant to high-purity aluminum are presented. The analysis starts with a summary of various contributions to the dc resistivity. It then goes on to demonstrate the quantitative relationship between the electrical and thermal conductivities. Finally, it considers the response of metals under ac conditions.

1. The dc Resistivity of Metals

The customary approximation used in the discussion of the resistivity of metals is Mathiessen's rule

$$\rho \approx \sum_i \rho_i \quad , \quad (1)$$

where ρ_i is the "partial" resistivity due to any one mechanism which inhibits the flow of electrons through the metal. In the next approximation, one can find deviation terms to be added to the right side of Eq. (1)⁵; however, they will not be considered in this paper. Equation (1), then, forms the basis for separate discussions of various contributions to the total electrical resistivity of a metal.

Data on the electrical resistivity of aluminum as a function of temperature are summarized in Fig. 1.⁶ Starting at low temperature, samples of different purity are seen to have different resistivities, independent of temperature. This is the region where localized imperfections in the atomic lattice dominate the total resistivity; various types of imperfections, and the separate contributions to the total resistivity are discussed in Section 1.A. As the sample temperature is raised, the resistivity of all samples finally begins to rise, following a common or universal curve for this

*This work was carried out at the National Bureau of Standards under the sponsorship of the Department of the Army and the Department of the Air Force.